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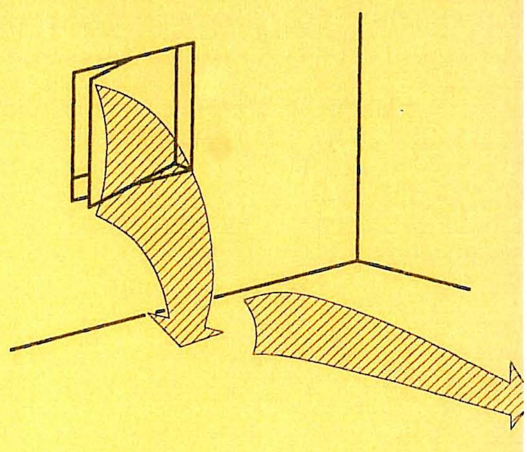

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CHARACTERISTICS OF BUOYANT FLOW FROM OPEN WINDOWS IN NATURALLY VENTILATED ROOMS

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ABSTRACT

An important element in the natural ventilation design procedure is the flow-pressure characteristics of a window with a given opening area. The flow in the room is another important element that is often ignored in the design phase due to lack of relevant information on the air movement. This paper shows the outcome of experiments with the room air distribution. The results show that the velocity distribution in the occupied zone can be described by a semiempirical model.

The buoyant cold flow from an open window will drop into the floor region of the room and cause a radial flow along the floor. It is possible to show that this flow behaves like the flow from wall-mounted diffusers for displacement ventilation. The velocity distribution can be described in the entire occupied zone as a function of the opening area, flow rate and temperature difference.

KEYWORDS

Natural ventilation, displacement ventilation, stratified flow, window, maximum air velocity, air distribution.

INTRODUCTION

Natural ventilation creates a flow of air into the room through openings in the building, see Heiselberg et al. (1999), for which reason an open window may be considered as a supply opening. This paper discusses the air movement that will take place in the occupied zone.

The buoyant cold flow from an open window will drop into the floor region of the room and cause a radial flow along the floor. This is a flow behaviour similar to the one obtained from a wall-mounted low velocity diffuser for displacement ventilation and, therefore, this paper begins with an introduction to this subject.

DISPLACEMENT FLOW FROM A WALL-MOUNTED DIFFUSER

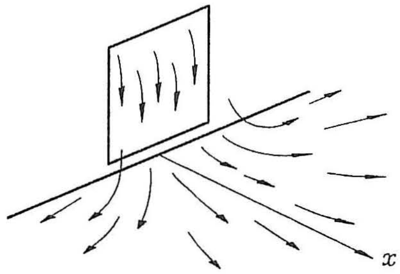


Figure 1: Air distribution in a room ventilated by displacement ventilation generated by a wall-mounted air terminal device.

The flow from a diffuser for displacement ventilation will be addressed in this chapter. Figure 1 shows how cold air from the diffuser drops into the floor region and causes a radial flow into the occupied zone. Measurements show that the entrainment into this stratified flow is small due to the vertical temperature gradient and they also show that the thickness δ of the cold layer is constant at high Archimedes numbers. The maximum air velocity u_x in a radial flow with constant thickness and zero entrainment will be inversely proportional to the distance x from the diffuser. Measurements confirm this behaviour and Nielsen (1992, 2000) has shown that the velocity u_x is given by

$$u_x = q_o K_{Dr} \frac{1}{x + x_o} \quad \text{(m/s)} \tag{1}$$

where q_o (m^3/s) is the flow rate from the diffuser. K_{Dr} is a variable which is a function of the type of diffuser and of the Archimedes number involved. (A large Archimedes number will give a reduced thickness and therefore a high velocity in the layer). Typical values of K_{Dr} are from 4 to 10 m^{-1}. x_o is the distance from the front of the diffuser to the origin of the radial flow. The virtual origin of the flow will often be located slightly behind the diffuser.

A small temperature difference between room temperature T_{oc} and supply temperature T_o will decrease the buoyancy effect and the flow will to some extent behave like a three-dimensional wall jet or a radial wall jet. (Entrainment is present, the momentum flow will be preserved and the thickness δ will be linear proportional to the distance $x + x_o$). The maximum velocity in this type of flow is given by Nielsen (1994)

$$u_x = const\ q_o \frac{1}{x + x_o} \quad \text{(m/s)} \tag{2}$$

It can be seen that the structure of Eqns. (1) and (2) is similar which implies that Eqn. (1) can be used as an empirical description for the whole temperature range.

NATURAL VENTILATION AND BUOYANT FLOW FROM AN OPEN WINDOW

The following measurements of air movements in a room have been made on a side-hung window located 1 m above the floor. The window has a width of 0.81 m and a height of 1.38 m. More details of the test setup and the general investigations of natural ventilation are given by Heiselberg et al. (1999).

The area of the opening a_o is defined as the smallest geometrical cross section for the flow through the window. Measurements have been made for a_o equal to 0.04 m^2 and 0.10 m^2 corresponding to an opening angle of 5 and 15 degrees.

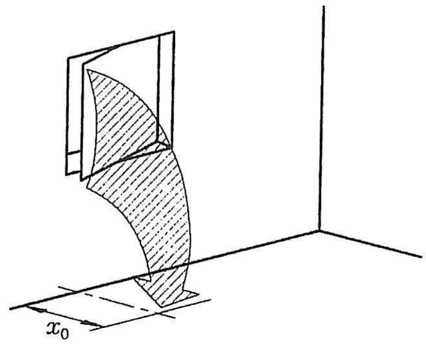


Figure 2: Buoyant cold flow from an open window in the case of single-sided natural ventilation.

Figure 2 shows that the first part of the flow from the window will act as a thermal jet. The distance x_o to the point where the jet reaches the floor will be dependent on the air flow rate (pressure difference) and the temperature difference. Determination of flow directions at different locations in the floor region gives the location of the virtual origin with a high degree of accuracy and it further shows that the flow along the floor is a semiradial flow. It is obvious that it is necessary to take the virtual origin in this flow into consideration. Figure 3 shows the distance x_o to the virtual origin versus the Archimedes number Ar'. x_o is defined as a negative quantity because the virtual origin is always located in front of the window.

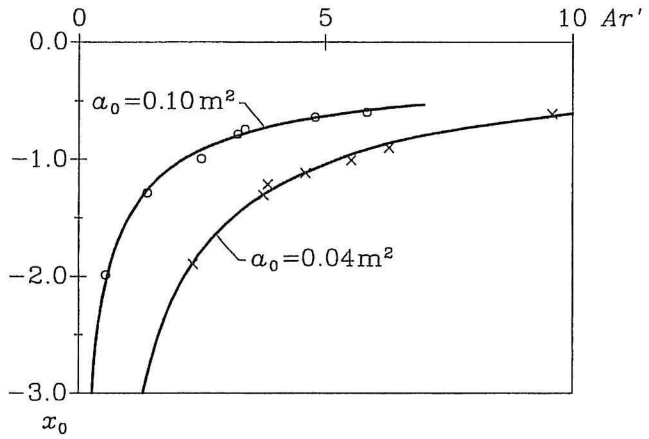


Figure 3: Distance x_o to the virtual origin versus Ar'.

Ar' is defined as

$$Ar' = \frac{T_{oc} - T_o}{q_o^2} 10^{-3} \quad (\mathrm{Ks^2/m^6}) \tag{3}$$

Ar' is not a dimensionless number as the conventional Archimedes number Ar but it has a similar structure. It is convenient to use variables with dimensions because it is possible to make a direct comparison with other types of flows in the occupied zone as shown in figure 6.

The velocity distribution in the radial flow along the floor is measured by a number of hot-spheres. The measured vertical velocity profiles are similar to the universal profile for a wall jet. The velocity u_x is defined as the maximum velocity measured along the floor in the direction of the main flow in the semiradial pattern that is established in the floor region. This direction is perpendicular to the window wall for the openings reported in this paper ($a_o \leq 0.10$ m^2).

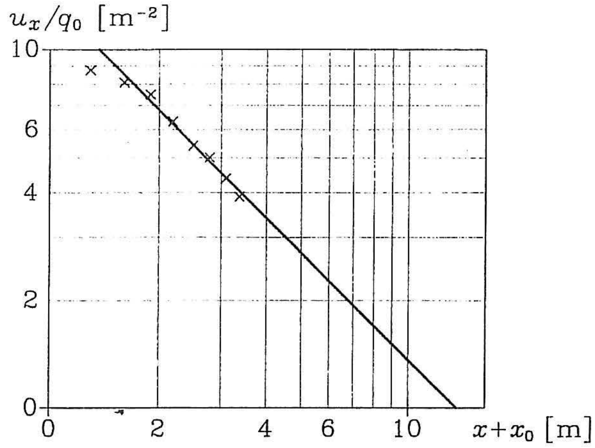


Figure 4: Log-log depiction of velocity u_x versus distance $x + x_o$. q_o = 148 m^3/h, a_o = 0.10 m^2 and Ar' = 3.39 Ks^2/m^6.

Figure 4 shows a typical set of u_x measurements. u_x is given as a function of $x + x_o$ and it is obvious that u_x is inversely proportional to $x + x_o$ because the slope of the velocity decay is -1.0 in the log-log graph. All measurements show this characteristic behaviour, which means that the maximum air velocity u_x can be described by an equation similar to Eqn. (1)

$$u_x = q_o K_w \frac{1}{x + x_o} \quad \text{(m/s)} \tag{4}$$

where x_o is given from Figure 3.

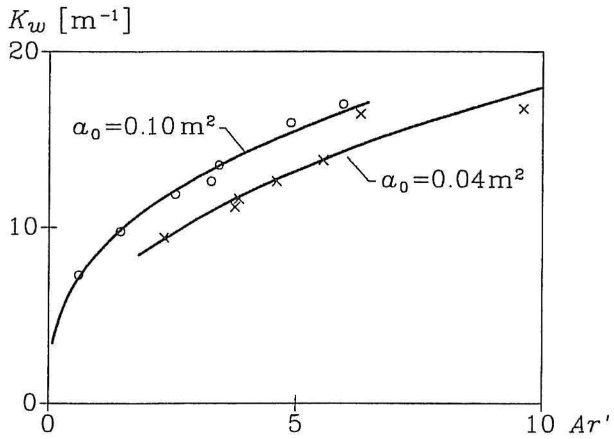


Figure 5: K_w versus Ar' and a_o for a side-hung window.

K_w is a constant which is dependent on the geometry of the test setup as e.g. type of window and location of window in the wall. It is also dependent on the degree of opening, a_o and on the flow rate and temperature difference. The last two variables can be expressed by Ar'. Figure 5 shows the values obtained for the side-hung window.

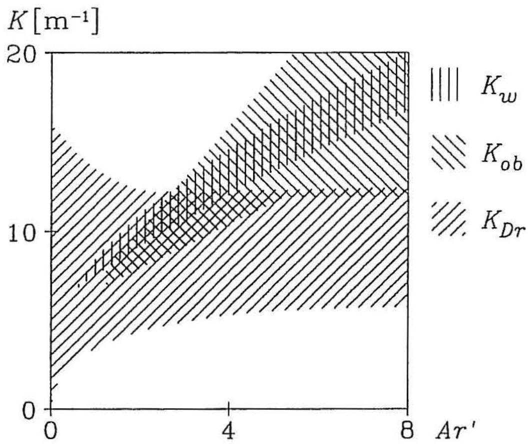
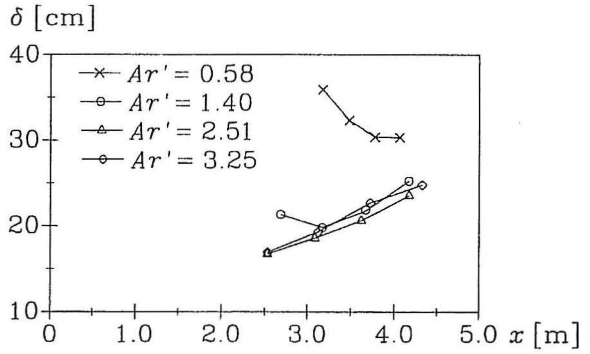


Figure 6: K-values for different types of radial flow. K_{Dr}: flow from wall-mounted diffuser. K_{ob}: flow from opening between obstacles in a room ventilated by displacement ventilation, K_w: flow from an open window.

It is surprising to see that K-values for different types of stratified and semistratified flow will have the same level, about 4 to 20 m^{-1}, as indicated in Figure 6 showing K-values for different types of flow. The flow from an open window behaves like the flow from an opening between obstacles in a room ventilated by displacement ventilation, K_{ob}, see Nielsen (1992, 2000). K_w has also the same level as K_{Dr} for the first generation of wall-mounted diffusers where the flow was directed into the occupied zone. It can be concluded from the Figures 3 and 6 that it is possible to develop openings for natural ventilation with improved characteristics compared with an open window. A device should generate a small negative or a positive x_o and it should have a K-factor in the level of 5 m^{-1} like a new diffuser for displacement ventilation. Such improvements will reduce the maximum velocity u_x in the occupied zone considerably compared with the level obtained by ventilation through a window.

Stratified flow will be in a subcritical state where the entrainment is diminishing as shown by Wilkinson and Wood (1971). A small entrainment rate corresponds to a small growth rate $d\delta/dx$ where δ is defined as the thickness of the layer up to the velocity $u_x/2$. Figure 7 shows δ as a function of the distance x from the end wall with the window. It is possible to find areas with a small growth rate but also areas with a growth rate close to 0.1, which is a typical value for an isothermal wall jet. Therefore, it is not possible to conclude that the flow is a fully stratified flow, but the question does not have any importance for the use of Eqn. (4) because this equation will always be valid as argued for in connection with the discussion on Eqns. (1) and (2).



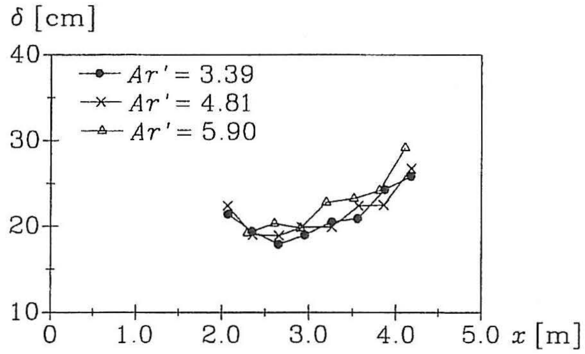


Figure 7: Thickness or length scale δ versus distance x in the flow along the floor.

CONCLUSIONS

Natural ventilation through an open window will create a flow of air into the ventilated room. The buoyant cold flow drops into the floor region and causes a radial air movement into the occupied zone. The maximum velocity in this air movement is proportional to the flow rate and is inversely proportional to the distance from the impact point of the cold air jet from the window. The velocity will be dependent on the type and location of the window, degree of opening and the Archimedes number.

Eqn. (4), Figure 3, and Figure 5 represent an example of a final design tool for the calculation of air velocity in the occupied zone in the case of single-sided natural ventilation with an open window.

It is possible to develop an opening for natural ventilation which will give a considerable reduction of the velocity level in the occupied zone compared with the value obtained by ventilation through a window.

REFERENCES

Heiselberg P., Dam H., Sørensen L. C., Nielsen P. V. and Svidt K. (1999). Characteristics of Air Flow through Windows. Presented at the First International One Day Forum on Natural and Hybrid Ventilation, HybVent Forum'99, 09/1999, Sydney, Australia.

Nielsen P. V. (1992). Velocity Distribution in the Flow from a Wall-Mounted Diffuser in Rooms with Displacement Ventilation. *Proc. of the Third International Conference on Air Distribution in Rooms.* ROOMVENT '92.

Nielsen P. V. (1994). Stratified Flow in a Room with Displacement Ventilation and Wall-Mounted Air Terminal Devices. *ASHRAE Transactions* **Vol. 100, Part 1**, 1163-1169.

Nielsen P. V. (2000). Velocity Distribution in a Room Ventilated by Displacement Ventilation and Wall-Mounted Air Terminal Devices. *Energy and Buildings* **Vol. 31, Issue 3,** Elsevier.

Wilkinson D. L. and Wood I. R. (1971). A Rapidly Varied Flow Phenomenon in a Two-Layer Flow. *J. Fluid Mech.* **47, Part 2**, 241-256.

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